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## Analysis of Tapial structures for modern use and conservation

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**ABSTRACT:** Tapial is an ancient form of rammed earth wall construction found in many parts of the world. In medieval Spain, Tapial was used in the construction of some large and complex structures, some many-storied. That these buildings remain standing (many remaining in use) is an indication of the durability of this form of construction, and is perhaps related to the climatic conditions found in central Spain. This paper describes an engineering study into an important structure in the Aragon region, significant parts of which are constructed in medieval Tapial, as well as other forms of construction. The aim of the study is both to improve understanding of the nature of this structure and to provide guidance on methods of preservation and new construction.

### 1 INTRODUCTION

Tapial is an ancient form of rammed earth wall construction found in many parts of the world. In medieval Spain, Tapial was used in the construction of some very large and complex structures. This paper is concerned with a particular set of buildings in Spain constructed with this technique.

The building under investigation here is the Preceptory at Ambel, Zaragoza in northern Spain which dates from the 10th century. (Part of the building is shown in Figure 1). It is made almost entirely from Rammed Earth (Tapial) and Adobe bricks. The archaeological

history of the building has been extensively studied by the 3rd author, (Gerrard 2003). It has, over time been used as a castle, monastery, palace, administration centre and farmhouse. The building has been modified a number of times, and at present has a number of large-scale visible structural faults which require repair.

### 2 DESCRIPTION OF BUILDING

Figure 2 shows a plan of the building at ground floor level. The earliest building on the site is a fortified tower built around 1100. This was constructed from large rammed earth blocks founded on large stones. Around 1250 living quarters were constructed, both with rammed earth walls 3 storeys high and 1m thick. By 1380 towers had been added to both buildings, reflecting a change in use to a more fortified role. At the same time a church was built at the south of the site.

By 1550 more rammed earth walled granaries were built at the north east of the site, up to 4 storeys high, and the church also was also extended. In 1636 the granaries were extended to the northwest corner, creating a courtyard in the centre. This was the last period of expansion, and by 1797 the building had fallen into disrepair. At that time the whole of the top floor on the north end was taken down, as were two of the 14th century towers. The roof was replaced on the north end of the building and repairs undertaken in the east granaries. By the 1960s two families were occupying the building, one in the northwest and the other in



Figure 1. Part of the Preceptory at Ambel.

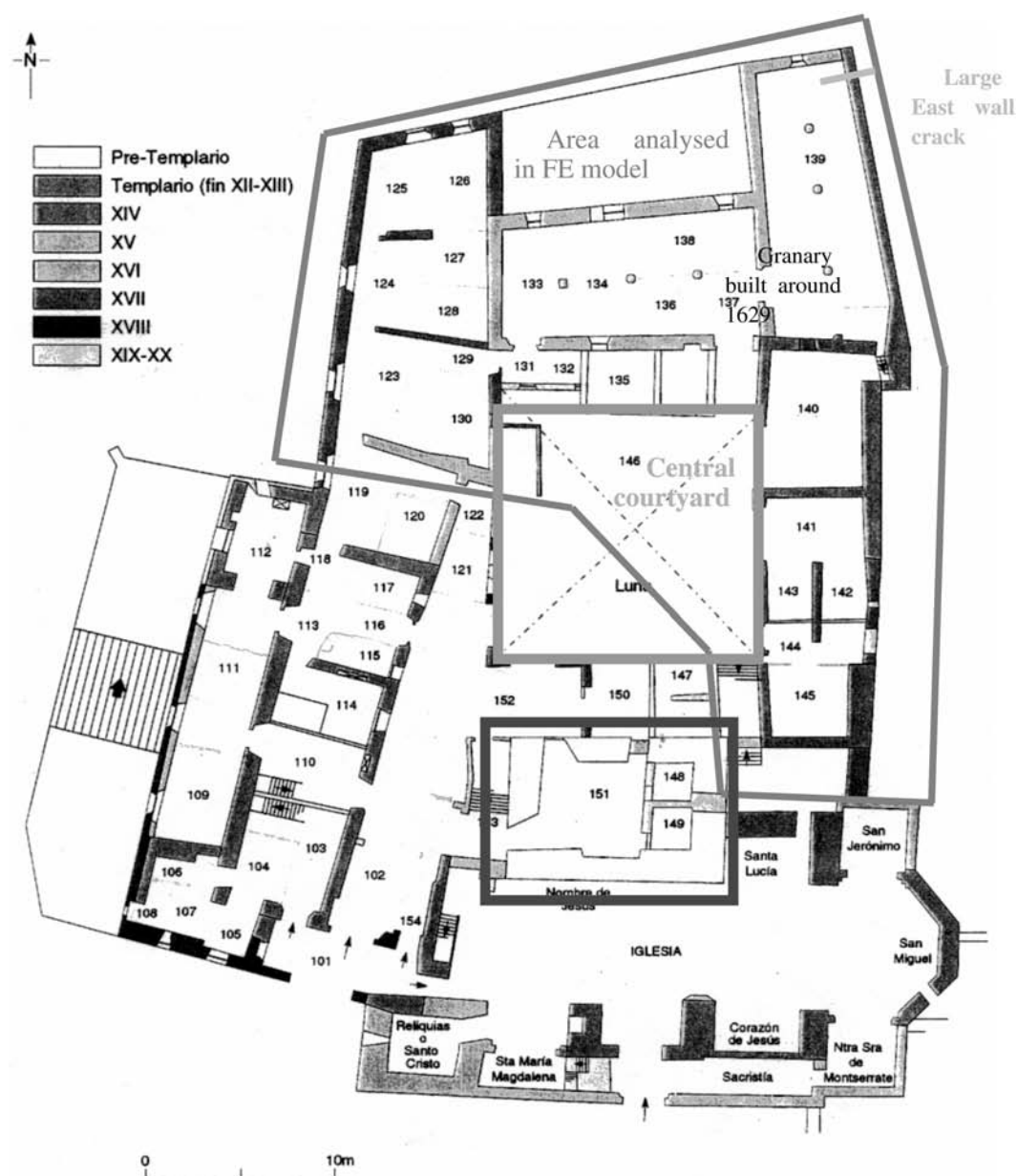


Figure 2. Plan of the Preceptory at Ambel.

the southwest wing. The building remained unoccupied until the early 1990s when a number of structural works were undertaken in order to make parts of the building habitable. At present there is large crack of unknown vintage at the north end of the northeast wall and a smaller, but growing crack in the eaves of the north courtyard wall.

### 3 RAMMED EARTH

In the building studied here, each surviving rammed earth block is around 2m long, by 1m square. Modern rammed earth blocks are constructed within formwork, which is removed and used to form the next block once one block is finished (Jest 1990).

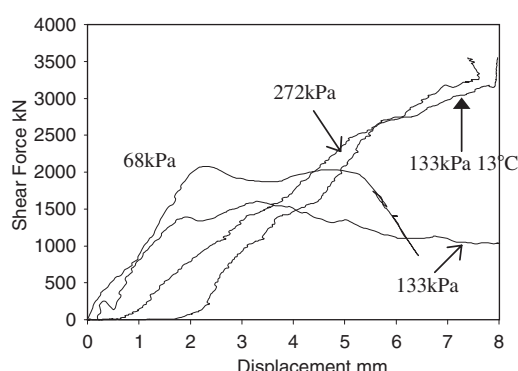


Figure 3. Shear box test results for rammed earth samples.

The formwork is usually constructed with wooden struts running through the wall, tying each side of the formwork together. These struts are removed along with the formwork, leaving holes running through the wall.

The formwork is filled with layers of earth approximately 0.1 m thick, with water sprinkled on each layer before it is compacted. Various substances can be added to the mixture, the most useful being lime, which forms a cement holding the particles together (Harrison 1990). In common with other masonry materials, rammed earth is strong in compression but weak in tension, so ties are also added to the mixture. The most common tie is straw, but human hair and bone have also been found within rammed earth walls. Windows and other orifices are cut after the construction of the wall. The roof is placed either directly on to the wall top, or onto a wooden beam fixed to the top of the wall, which will prevent water ingress. Finally the whole structure is plastered in a lime-based mix which provides an impermeable barrier, while still allowing the structure to 'breathe'.

#### 4 SAMPLING AT AMBEL

Rammed earth samples were taken from various parts of the building and tested using the simple shear box test. In some instances it was impossible to recover an intact 60 mm square specimen but in all cases testing was carried out with an intact sample crossing the shear plane.

The results are inconclusive as the plots of shear stress against displacement in Figure 3 shows. Three tests were carried out on samples thought to date from the 19th century and one on a 13th century sample. In the latter samples, a lower peak shear strength is reached in the sample subjected to a higher normal stress, contrary to expectations for standard frictional

materials. For example, predicted angles of friction for the first two samples are  $83^\circ$  and  $72^\circ$  indicating bonding to be significant. The 19th century sample at the highest normal stress, however, does not show a peak strength within the range of testing carried out. The 13th century sample also fails to show a peak strength.

These limited set of tests show that rammed earth is clearly not a simple frictional material but could be regarded as a frictional bonded soil. Clearly a comprehensive sampling and testing programme is required to confirm properties of this material that can be used reliably.

#### 5 FINITE ELEMENT MODELLING

A survey of the building was undertaken in 1956, and plans produced following the survey were used in this study to construct a 3D CAD drawing of the structure. The floor plans were used in conjunction with recent drawings of each of the faces of the structure in order to place openings at the correct height (Gerrard 2003).

The finite element package *Strand7*© was used to generate a mesh of the building walls using four-noded tetrahedral elements from this CAD model. While these elements are not the most accurate in modelling terms, enough clarity is provided to undertake a basic structural analysis of the building. Also for simplicity at this stage, linear elastic material behaviour was assumed throughout.

The loads applied by the roof to the top of the walls were then applied in the FE model and gravity 'turned on'. The structure was initially modelled as homogeneous with the required values of elastic modulus and density based on laboratory testing. A Poisson's ratio of 0.2 was considered suitable.

##### 5.1 The selected modelled area

It was decided to model only part of the structure, as the whole building has around 136 rooms on 4 floors. The north wing of the building (Figure 2) was singled out for more detailed study as this area contains the worst structural defects and is at present uninhabited.

There are two major factors which are not immediately obvious but may have a large bearing on the structural analysis of the structure, these are the fact that a 'step' runs through the site meaning that the most southern ends of the modelled part are built on high ground, with the northern ends built directly onto the lower ground, so that there is a basement at the north end which is solid rock at the southern end. Secondly, a tower built in 1380 was removed in 1796, when the structure was saved from major structural collapse by the removal of the highest storey and other structural repairs.

## 5.2 CAD and finite element model

In order to simplify drawing and analysis, some assumptions were made. Only structural walls were modelled, and the building was modelled as homogeneous in its present state. No account was taken of different wall ages and properties such as elastic modulus, and density were considered uniform throughout the building. This homogeneity removes the need to model the joints between the different ages, the movement and stiffness of which would be extremely difficult to measure and to quantify.

There is also no account taken of the wall-floor interactions, the floors consist of timber beams with an earth infill on a plaster ceiling. This system is around the same density as used for the modelling of rammed earth, but will be significantly stronger in bending and in tension. The joint may also provide some stiffness and redistribution of moment, but again this is very difficult to measure and to quantify. Further aspects of the modelling were as follows:

- The roof loading calculated using a uniform density over a calculated projected area.
- The base of the structure was modelled as being fully fixed, although this approach takes no account of settlement which may have occurred, which may be one of the reasons for the crack appearing in the north east wall.
- The southeast wing of the structure, which is the oldest and is built onto solid rock, is modelled as being fully fixed.
- No account is taken of the courtyard in the centre of the structure, which is composed of fill material, which imparts a lateral earth pressure onto the south-facing wall of the north wing.
- The walls are also modelled as being vertical. While this is not the case, it is considered that the self-weight of the walls is sufficient to prevent overturning, and that simple buckling will not occur.

## 6 COMPUTER RESULTS

A number of modelled simulations were carried out using the model described above. Initially the structure was modelled as uncracked, to determine locations of stress concentration. Two cracked simulations were then carried out, with and without the self-weight considered. The cracks were modelled simply as gaps in the finite element mesh, so no force could be transferred, but as a linear elastic simulation was carried out, the cracks were not allowed to extend. The main parameter of concern was that of vertical normal stress ( $\sigma_y$ ), as the structural action is considered to be mainly compressive.

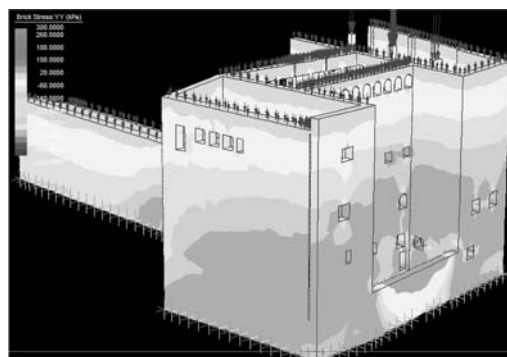


Figure 4. FE model of the building with vertical normal stress contouring.

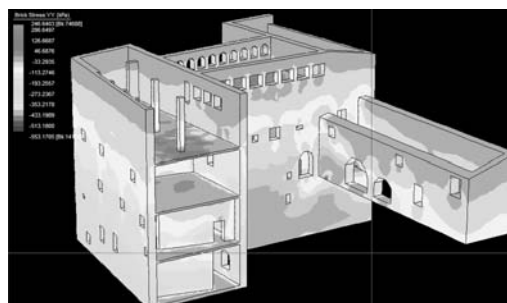


Figure 5. FE model view of the rear of the building.

### 6.1 Finite element model – roof loading and gravity

As an example of the FE modelling, Figure 4 shows the outline of the finite element model used with vertical stresses due to roof loading only and gravity. The stresses range from 0.3 MPa to  $-0.5$  MPa with tension positive. It can be seen that the stresses generally increase down the building, due to the high self-weight of the walls.

Figure 5 shows the building from the south, and detailed inspection reveals raised levels of tensile stress between columns of the windows at the top of the building, and also at the floor area around the rear column in room 302. Although the vertical stresses are plotted, the floor is also carrying substantial stresses in the other two directions. The high stresses at this location are due to the floor acting as a transfer beam, as there is no support below. It can be seen by looking at the original plans that this wall is part of a 13th century tower which has been consumed by the building of the 18th century part (that part below room 303). Undoubtedly some of the effects are caused by the idealisations assumed in the modelling, especially the

introduction of the cut line to the model. On a practical level, however, the model demonstrates that this floor should be checked for cracking and deformation, as the whole column load is being transferred through this floor.

## 6.2 Comments on the accuracy of the model

It is accepted that the computer model is crude. However, the actual structure is highly complex and would be almost impossible to model completely accurately. There are certain features which should be considered were the model to be constructed more accurately.

The magnitudes of the stresses obtained from the FE model show that the building will not fail in compression, when compared to unconfined compressive strength values quoted by Walker (1999) and Houben and Guillard (1992). One particular aspect that has not been modelled is the settlement which may have occurred underneath the east tower, this could be a reason for the base of the wall falling forward.

A linear elastic analysis was carried out, which does not model failure. However as the building is being modelled in its present state (not failing) this is, perhaps, a reasonable assumption to make. Modelling brittle materials using conventional finite element approaches is difficult. An alternative would be the use of discrete element modelling assessment of defects.

The site survey undertaken by the first author in 2003 identified a number of structural defects. Some of these are discussed below, together with possible solutions.

## 6.3 Crack in the north east wall

Figure 6 shows the northeast wall of the building where a major crack is visible. This appears to be the worst crack in the building. Externally, the crack runs between the brick quoins which form the corners of the building, but at around 2/3rds height the main crack stops and another crack extends upwards through the brickwork and into the exposed earth. A further crack is visible to the left, running through the earth, but this is not visible within the building. The wall was built in a number of stages and has also been subjected to numerous repairs and alterations. The base of the wall was built around 1380 and extends the full distance across the front of the building. A second level was built sometime before 1550 and is fronted entirely with brick, although there appears to be a step just to the left of the ivy. A third building phase resulted in brick quoins extending the full height, with a rammed earth wall in between. This final stage actually extended one storey higher than at present and was removed during the building renovation in 1796 (Gerrard 2003).

The bottom of the north wall is leaning forward slightly when compared to the adjacent building in



Figure 6. View of major crack in the NE wall.

which was constructed in 1960 which can be assumed to be vertical. It is assumed that the next stage of building commenced onto an already leaning wall, and that the top sections of the wall are indeed vertical. There is however the possibility that the top of the north wall is falling forward, away from the building as it does not appear tied to the other walls at the top. It is assumed that originally the top storey tied the north wall into the structure, but following the removal of the top storey, the north wall is now unsupported.

There is also no connection between the floors and the north wall as the ceiling beams run east-west, tying the east and west walls together, but allowing the north and south walls to act independently. These rooms have been used as granaries for most of their lives, therefore will have been subjected to high loading and unloading cycles, and the floor could easily have failed given the high loading. However the cracking pattern in the floor is not consistent with slab failure given a load on the whole area, but is consistent with the floor being loaded very unevenly.

The top storey was removed in order to prevent major structural collapse (Gerrard 2003). This would indicate that the cracking in the east wall were already present. What is not known is if the cracking has been stopped or dramatically reduced since 1796, is the

crack 'stable'. This can partly be guessed at by looking at the floor pattern in room 237 which reveals that there have been two major failures of the floor, with the tiling pattern changes indicating a repair. Therefore it can be assumed that the floor failed first in the centre of the room and was repaired, although beam failure rather than wall movement may have caused this collapse. Secondly the floor failed again, the crack is still present, and has been repaired by the placing of a wooden beam into the western wall. This repair probably occurred around 1800 although it is difficult to date exactly.

#### 6.4 *Modelling of the north wall*

The computer model constructed in order to study stress paths shows that there is no tension developed around the cracked area, but this model can be shown to be inaccurate in that the base of the wall is modelled as being perfectly vertical, whereas actually it is leaning forward slightly. This system would tend to develop tensile stresses in the top of the wall, which have not been picked up by the model. There has been no modelling of the different materials in the wall, as a finite element model has been used, there is no distinction made between the brick quoins and the rammed earth wall. It is not known whether the quoins in the corners are fully constructed or are simply fronted with bricks, and this fact would significantly alter the structural properties.

#### 6.5 *Settlement*

The reason for the initial crack is difficult to pinpoint, but one reason could be settlement of the made ground on which the wall is based. The land is sloping gently down to the north, with a made stone base upon which the rammed earth wall is built. A stream has been running across the north of the site for at least 1000 years, and while this is not very large, it is conceivable that this stream may have caused erosion, flooding or other activity leading to subsidence of the ground immediately under the tower. As the ground is already sloping, it is conceivable that the original builders made the level up in order to build the first level of the wall, which acted as a one storey building, and backs onto solid rock. After a number of years this wall was built up to three storeys, then again built up to 5 storeys. From the change in angle, it can be seen that the leaning forward of the wall occurred before 1380 and following this around 1550 the remainder of the wall was built.

#### 6.6 *Recommendations*

The best method to prevent the cracks propagating is to pull the two surfaces closer together, but this must be

done in such a way that no further harmful stresses are developed. At present there is little published material on the structural stabilisation of rammed earth structures, although much has been published on new build, and there are many specific examples of restoration work. The present solution involves the bolting of steel I beams to the transverse roof timbers, which are then tensioned against H shaped bars fixed against the outside of the building. This solution, while appearing to work, is not ideal, in that the whole overturning force of the north wall is taken on the timber beams, and that there is a large visual impact on the front of the building.

The authors considered a number of solutions. Grouted reinforcement bars could be inserted into the north wall and travel through into the east wall. These bars could either be anchored externally in a similar fashion to the H bars present at the moment, or may be able to provide enough resistance though application of grout.

Problems involved with this technique include the fact that it has never been tried before in rammed earth structures, and tests would have to be carried out in order to ascertain the pullout strength of the reinforcement bar (the tensile capacity of the joint) and the effect of drilling a long hole into rammed earth. However this solution would prevent the load being transferred to the roof beams, and should be considered if there appears to be any failure of the roof bolts.

A tested retrofitting technique is the application of nylon strapping to provide tensile support across the crack. This strapping would have to be bolted into place, and again the effect of bolting structural elements into existing walls has never been thoroughly investigated, but would provide an easy and cheap solution to cracking in rammed earth walls.

## 7 CONCLUSIONS

This paper presents aspects of a much larger study of an interesting heritage structure in Spain, built mainly of rammed earth.

The FE model used here has highlighted some of the difficulties in modelling historic structures. This is perhaps outweighed by the fact that a 3D model allows structural mechanisms to be identified which would be difficult to spot on 2D drawings. Finite elements were considered to be the simplest method for the modelling of rammed earth as it can be considered as homogeneous. Discrete elements would be more useful in modelling the interactions between the rammed earth and adobe bricks.

This project has drawn together many aspects of engineering including site investigation, laboratory testing and computer modelling. It has looked at a

specific structure in Spain and recommended solutions to some of the structural problems present.

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